TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
CIVIL ENGINEERING | BUDOWNICTWO

2-B/2015

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RELATIONSHIP BETWEEN SURFACE ROUGHNESS AND TURBULENCE OF NATURAL WINDS NEAR THE GROUND SURFACE

ZWIĄZEK MIĘDZY CHROPOWATOŚCIĄ I TURBULENCJĄ NATURALNYCH WIATRÓW W WARSTWIE PRZYZIEMNEJ

A b s t r a c t

The design of low-rise buildings such that they can handle wind loads makes it necessary to accurately evaluate those wind loads, both on the structural framework and on the cladding/components. To this end, it is necessary to fully understand the characteristics of the wind near the ground around a building. This study sets out to develop a quantitative means of estimating the turbulence of the wind near the surface of the ground, based on field measurements obtained at different points across Japan. The surface roughness is evaluated based on several factors taken from a building information database. The relationship between these factors and the turbulence of the wind is discussed. The effect of the observation height, relative to the surface of the ground, on the turbulence is also investigated.

Keywords: *gust factor, surface roughness, building information database, field measurement, observation height*

S t r e s z c z e n i e

Projektowanie niskich budynków w taki sposób, aby opierały się one działaniu wiatru, wymaga dokładnej oceny obciążenia wiatrem zarówno konstrukcji, jak i elementów pokrycia. W tym celu konieczne jest pełne zrozumienie charakterystyk wiatru w warstwie przyziemnej w pobliżu budynku. W niniejszej pracy podjęto próbę oszacowania wielkości turbulencji wiatru w pobliżu powierzchni w oparciu o pomiary w terenie w różnych punktach na obszarze Japonii. Chropowatość powierzchni została wyznaczona na podstawie kilku parametrów przyjętych na podstawie baz danych informacji o budynkach. Omówiony został związek między tymi czynnikami i turbulencją. Analizowano także wpływ wysokości nad powierzchnią podłoża, na której prowadzona jest obserwacja na turbulencję.

Słowa kluczowe: *współczynnik działania porywów wiatru, chropowatość powierzchni, bazy danych informacji o budynkach, pomiary terenowe, wysokość obserwacyjna*

DOI: 10.4467/2353737XCT.15.140.4177

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1. Introduction

The wind-resistant design of low-rise buildings makes it necessary to understand the characteristics of the wind near the surface of the ground around those buildings, e.g., the mean wind-speed profiles, the turbulence intensity, and the gust factor. In the AIJ Recommendations for Loads on Buildings [2] and the Building Standard Law of Japan, the mean wind speed profile is specified as being constant up to a specific height Z_b, corresponding to the surface roughness category, beyond which it is expressed by a power function of height Z above the ground. The turbulence intensity profile is also specified, much like the mean wind speed in the AIJ Recommendations [2]. Such vertical profiles may significantly overestimate the wind loads on low-rise buildings, both on the structural framework and on the cladding/components. To evaluate the design wind loads, the characteristics of the wind near the surface of the ground should be fully understood.

The goal of this study was to develop a quantitative means of estimation for assessing the turbulence of the wind near the surface of the ground, based on field measurements made at many locations across Japan. The relationship between the characteristics of the surface roughness and the turbulence of wind is discussed. Special attention is paid to the gust factor in this paper.

2. Characteristics of surface roughness

2.1. Measured data

In the AIJ Recommendations [2], surface roughness is divided into five categories, I to V. The profile of the turbulence intensity I_Z is specified as follows:

$$I_Z = \begin{cases} 0.1\left(\dfrac{Z}{Z_G}\right)^{-\alpha-0.05} & Z_b < Z \le Z_G \\ 0.1\left(\dfrac{Z_b}{Z_G}\right)^{-\alpha-0.05} & Z \le Z_b \end{cases} \qquad (1)$$

where Z represents the height above the ground [m]; α, Z_G, and Z_b are the parameters defining the profile, the values of which are listed in Table 1.

Fig. 1 shows the turbulence intensity profiles for the five surface roughness categories. The value of I_z is specified as being constant up to a height Z_b, according to the category.

Full-scale measurements of the wind speed near the surface of the ground were carried out at various sites with different terrains; in most cases, the measurement height was less than Z_b. Similar measurements were performed at many Japan Meteorological Agency (JMA) meteorological observatories and Automated Meteorological Data Acquisition System (AMeDAS) sites. Wind data from as many as 243 observation sites across Japan were used for this study. The observation height ranged from 5 m to about 70 m, as shown in Fig. 2. In most cases, the observation height was less than 15 m. The data were used to analyze the characteristics of the wind near the surface of the ground, e.g., the intensity and scale of the turbulence, the power spectrum, and the peak factor. The dependence of these factors on the observation height as well as on the surface roughness of the upwind area is discussed.

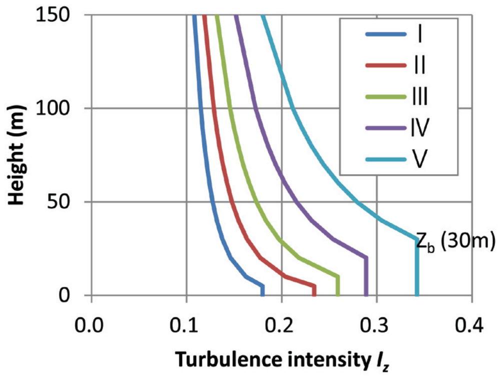


Fig. 1. Turbulence intensity profiles

Table 1

Parameters for defining turbulence intensity profile

Category	I	II	III	IV	V
α	0.10	0.15	0.20	0.27	0.35
Z_G [m]	250	350	450	550	650
Z_b [m]	5	5	10	20	30

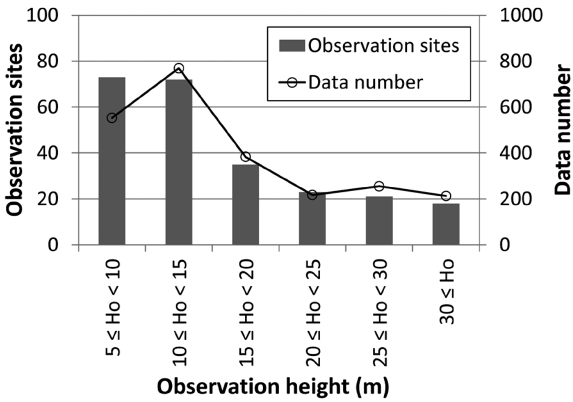


Fig. 2. Histograms of numbers of observation sites and data used in the present study

For this study, data collected over the course of one year at each point were used. The wind speed and direction were sampled at a rate of 4 Hz, and a moving average of 3 s was applied to the data. Data for which the 10-min mean wind speed is higher than a predetermined value (3 to 5 m/s) corresponding to the observation height (H_O) were used.

Approximately 75% of the data was obtained from the JMA and AMeDAS sites. For these databases, only statistical values have been published, e.g., the 10-min average wind speed and the 3-s average wind speed. Therefore, as the first step, the gust factor (G_F), defined as the ratio between the 3-s average wind speed and the 10-min average wind speed, is investigated.

2.2. Analysis area

The characteristics of the surface roughness near the observation sites significantly affect the characteristics of the wind speed and direction. For this analysis, we focused on the 16 upwind trapezoidal areas defined as shown in Fig. 3. The length of the area is 200 m, and the width changes from 50 m to 110 m in the upwind direction. Our previous study [1] indicates that this area is appropriate for discussing the relationship between the surface roughness and the turbulence of the wind near the ground.

Up to 2390 sets of data were used in this study, as illustrated in Fig. 2. The gust factor was calculated from these data.

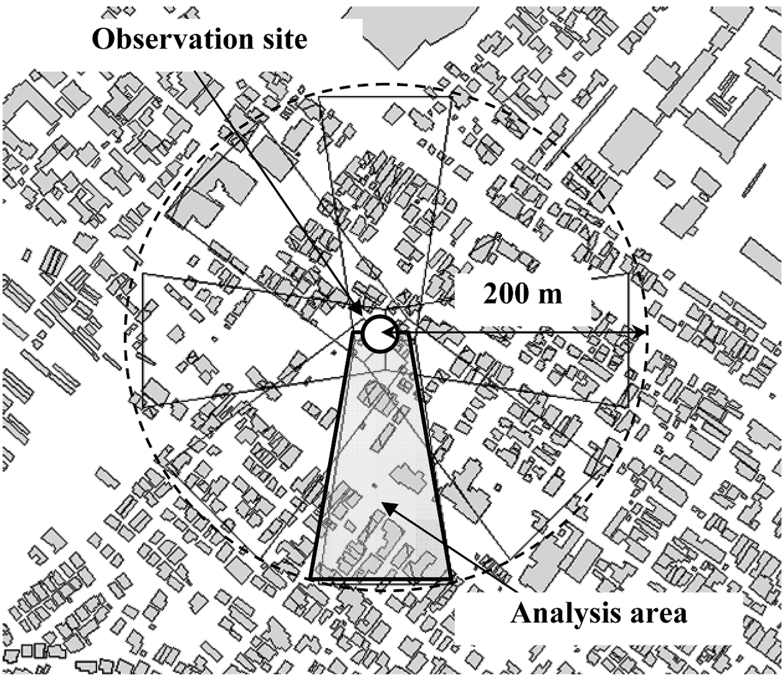


Fig. 3. Analysis area

2.3. Definition of surface roughness factors

Surface roughness is characterized by many factors, including the building coverage ratio, the average height of the building, and the building volume. The eight major surface roughness factors are defined in Table 2 and by Eqs. (2) to (9). The details of these factors are presented in [1, 3]. In this study, a "high building" refers to a building with more than four stories. The values of these factors are evaluated by using a building information database.

Table 2

Surface roughness factors

Average height of building [m]	$\overline{h} = \left(\sum_{i=1}^{n} h_i\right) / n$	(2)
Average area of building [m^2]	$\overline{a_{bi}} = \left(\sum_{i=1}^{n} a_{bi}\right) / n$	(3)
Average volume of building [m^3]	$\overline{V_{bi}} = \left(\sum_{i=1}^{n} a_{bi} h_i\right) / n$	(4)
Building coverage ratio [–]	$R_b = \left(\sum_{i=1}^{n} a_{bi}\right) / A$	(5)
Building volume ratio [m]	$V_b = \left(\sum_{i=1}^{n} a_{bi} h_i\right) / A$	(6)
Density of building volume [–]	$V_D = \left(\sum_{i=1}^{n} a_{bi} h_i\right) / A\overline{h}$	(7)
Ratio of high buildings [–]	$H_4 = \left(\sum_{i=1}^{n} n_{\geq 4}\right) / n$	(8)
Ratio of high building area [–]	$\overline{h_4} = \left(\sum_{i=1}^{n} a_{\geq 4}\right) / A$	(9)

where h_i represents the height of each building (m); a_{bi} is the area of each building (m^2); $a_{\geq 4}$ is the area of a high building (m^2); A is the analysis area (m^2); n is the number of buildings (–); $n_{\geq 4}$ is the number of high buildings (–) in the area under consideration.

The correlation coefficients between pairs of factors among these eight factors are listed in Table 3. It can be seen that the correlations between R_b and V_b, $\overline{h}$ and H_4, V_b and V_D, and V_b and $\overline{h_4}$ can be as high as 0.89, 0.81, 0.80, and 0.80, respectively. On the other hand, the correlations between $\overline{a_{bi}}$ and the other factors are generally low. Therefore, in this study, focus is on R_b, V_b, $\overline{h}$, and $\overline{h_4}$.

Table 3

Correlation coefficient of eight factors

	$\overline{h}$	$\overline{a_{bi}}$	$\overline{V_{bi}}$	R_b	V_b	V_D	H_4	$\overline{h_4}$
$\overline{h}$	–	0.32	0.66	0.31	0.58	0.37	0.81	0.52
$\overline{a_{bi}}$	0.32	–	0.58	0.25	0.28	0.23	0.28	0.21
$\overline{V_{bi}}$	0.66	0.58	–	0.19	0.69	0.32	0.55	0.46
R_b	0.31	0.25	0.19	–	0.59	0.89	0.22	0.45
V_b	0.58	0.28	0.69	0.59	–	0.80	0.56	0.80
V_D	0.37	0.23	0.32	0.89	0.80	–	0.32	0.66
H_4	0.81	0.28	0.55	0.22	0.56	0.32	–	0.72
$\overline{h_4}$	0.52	0.21	0.46	0.45	0.80	0.66	0.72	–

Fig. 4 represents the relative frequency distributions of R_b, V_b, $\overline{h}$, and $\overline{h_4}$ for all of the observation sites. It was found that the distribution pattern of the relative frequency is highly dependent on these factors. As illustrated in Figs. 4(a) and 4(b), the values of R_b and V_b are distributed almost uniformly within the range of 0 to 0.4. Therefore, these two factors seem to be closely related to the turbulence of the wind. In the Tokyo Metropolitan area, the value of R_b varies from 0.1 to 0.5, while approximately 90% of the data ranges from 0.15 to 0.40 [3]. In this study, data obtained at many locations in both suburban and rural areas is included. By comparison, the range of $\overline{h}$ and $\overline{h_4}$ is relatively narrow, as shown in Figs. 4(c) and 4(d). These values change relatively little. Because the building height is not included in the building information database that was used for this study, the height of a story was assumed to be 3 m for every building. There are many 2-story buildings, such as residential houses, in most areas. Therefore, the relative frequency of 6 m is fairly high for $\overline{h}$. Fig. 4(d) indicates that the number of high buildings is relatively small.

Fig. 5 represents four areas (shaded areas) with different R_b values from 0.1 to 0.4, in which 16 areas, each corresponding to a different direction, are also shown. The terrain categories defined by AIJ and the values of several surface roughness factors from A to D are shown in Table 4. It was found that these factors generally increase with an increase in R_b. However, sites where there are only a few large buildings, and the values of $\overline{h}$ and $\overline{h_4}$ are large despite the value of R_b being small should be considered.

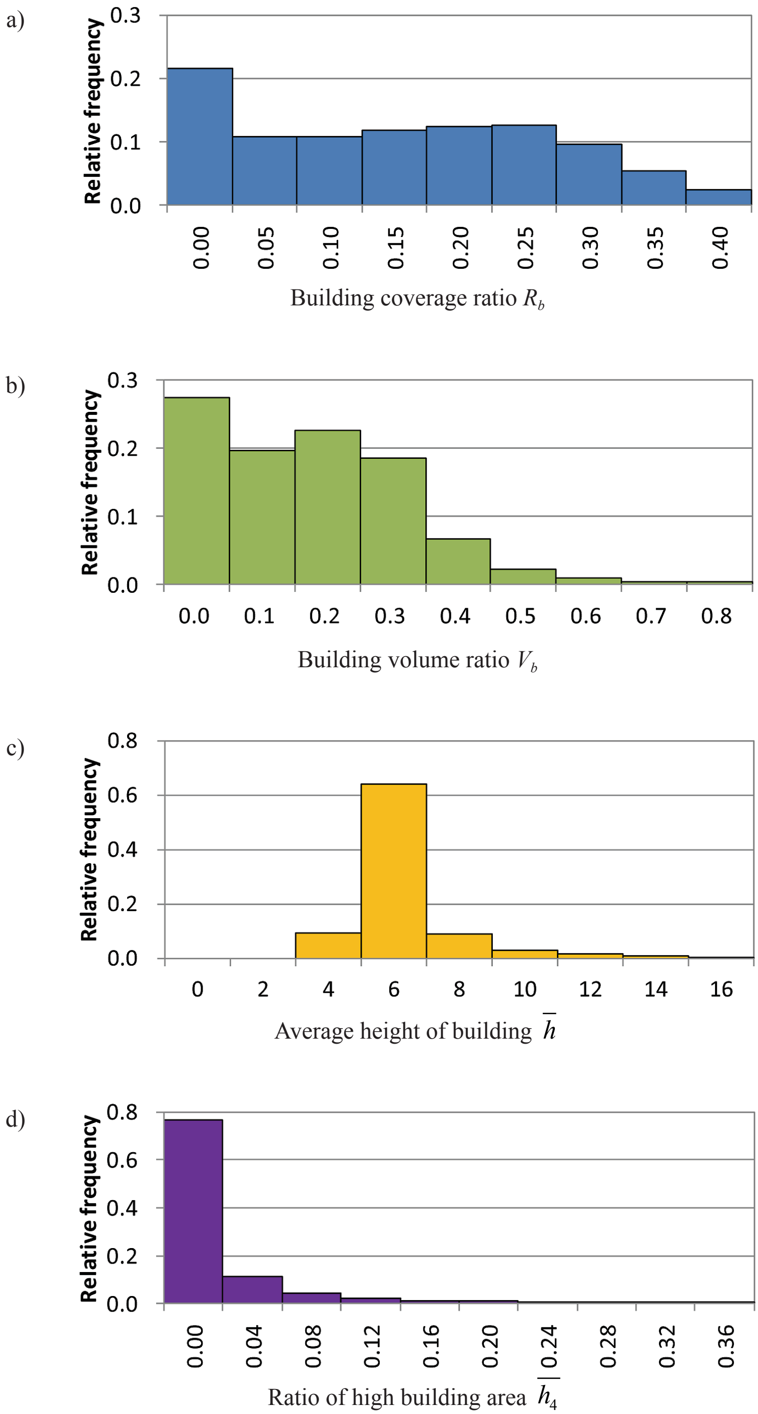
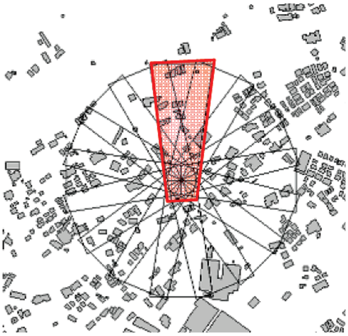
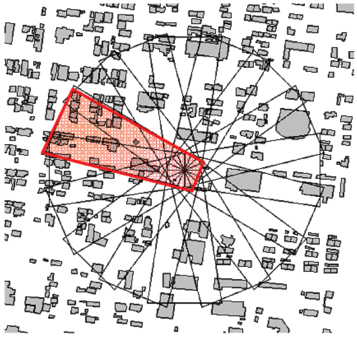


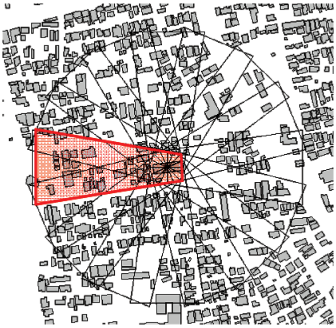
Fig. 4. Relative frequency distributions of R_b, V_b, $\overline{h}$, and $\overline{h_4}$



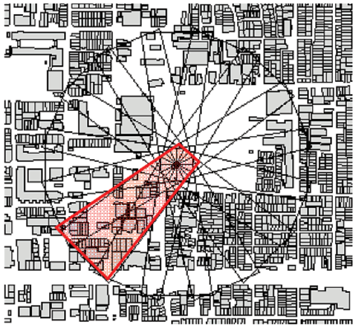
(a) Site A, $R_b = 0.1$



(b) Site B, $R_b = 0.2$



(c) Site C, $R_b = 0.3$



(d) Site D, $R_b = 0.4$

Fig. 5. Arrangement of buildings in four areas with different R_b values

Table 4

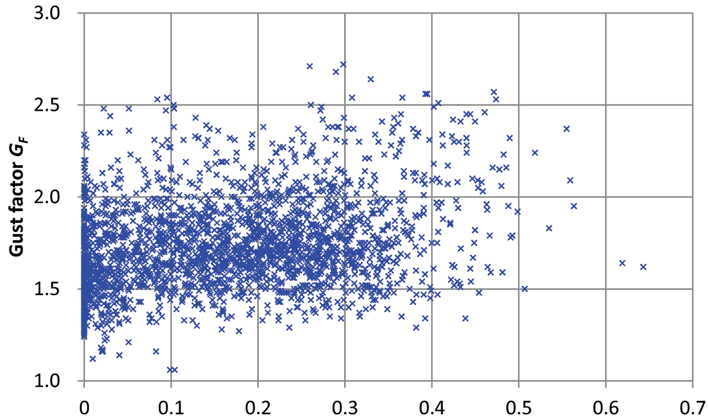
Values of surface roughness for the four sites

Site	A	B	C	D
Category (AIJ)	II	II	III	III
Wind direction	N	WNW	W	SW
$\overline{h}$ (m)	6.0	6.0	6.2	6.8
$\overline{a_{bi}}$ (m^2)	72	84	78	90
$\overline{V_{bi}}$ (m^3)	433	504	501	615
R_b	0.10	0.20	0.30	0.40
V_D	0.10	0.20	0.31	0.40
$\overline{h_4}$	0.00	0.00	0.01	0.03

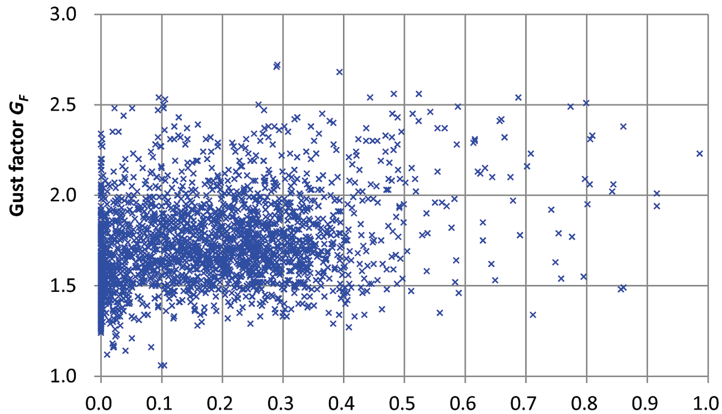
3. Gust factor

3.1. Relationship between surface roughness and gust factor

The relationship between G_F and surface roughness was investigated based on the above mentioned analysis. Figs. 6(a) and 6(b) show the dependence of G_F on R_b and V_b, respectively, for all the data. Although the data exhibit scattering, a trend whereby the value of G_F first increases slightly and then reaches an upper limit as the values of R_b and V_b increase can be identified. A similar trend was observed for the relationship between G_F and the other factors, e.g., $\bar{h}$ and $\bar{h}_4$ [4]. Note that the data for a wide range of H_O values, from 5 m to about 95 m, are plotted in Fig. 6.



(a) Building coverage ratio R_b

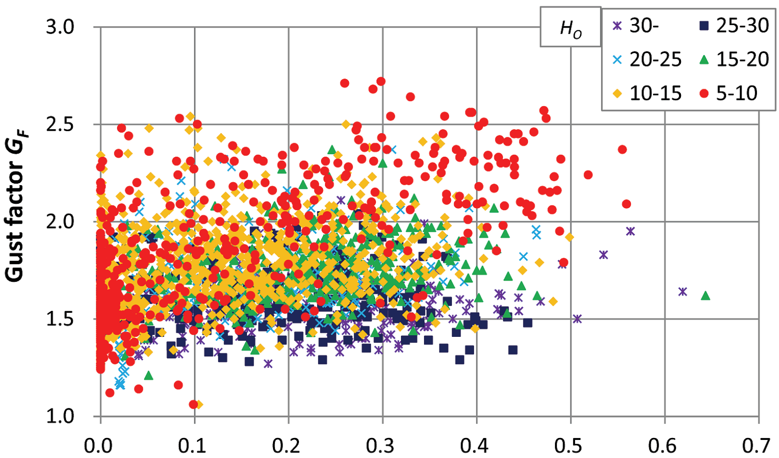


(b) Building volume ratio V_b

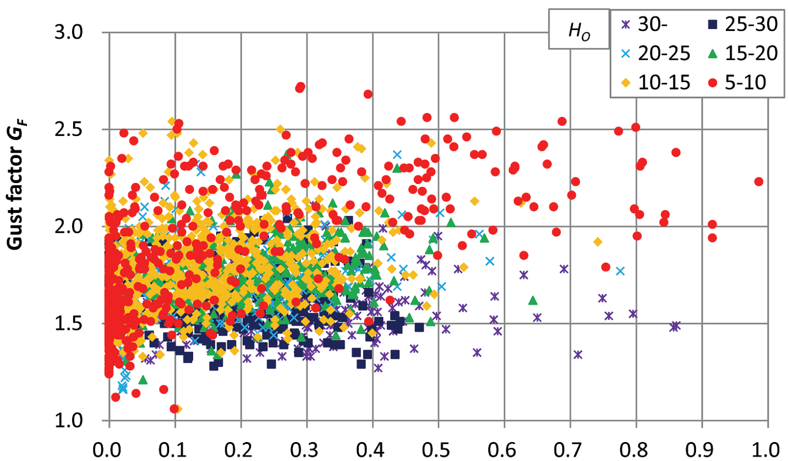
Fig. 6. Relationship between G_F and surface roughness

3.2. Influence of observation height on gust factor

The turbulence of the wind is also dependent on the observation height H_O. In this analysis, we classified the data into several heights, with a spread of 5 m. Fig. 7 shows the dependence of G_F on R_b, V_b, $\overline{h}$, and $\overline{h_4}$ for each height class. Although the results exhibit scattering, the value of G_F generally increases as the value of H_O decreases. The value of G_F seems to increase with R_b and V_b (see Figs. 7(a) and 7(b)). For $\overline{h}$ and $\overline{h_4}$, on the other hand, no dependence of G_F on these factors was observed. This may be due to the fact that the range of these factors that could be used for this study is rather limited.

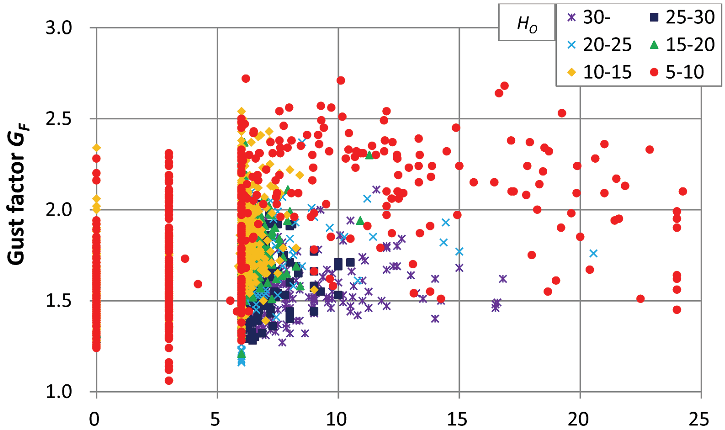


(a) Building coverage ratio R_b

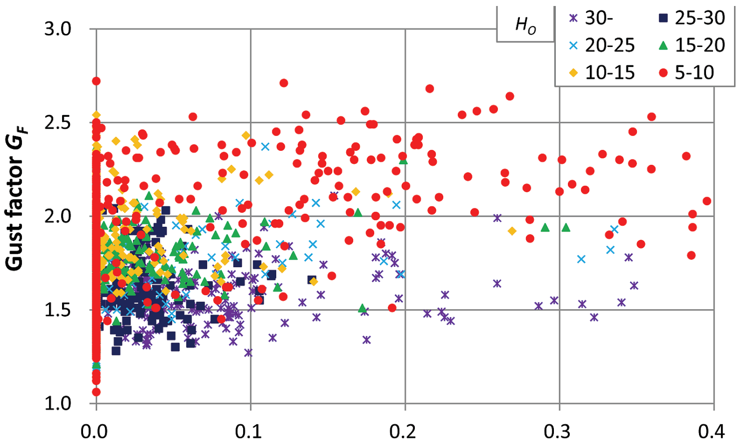


(b) Building volume ratio V_b

Fig. 7. Relationship between G_F and surface roughness classified into several height classes



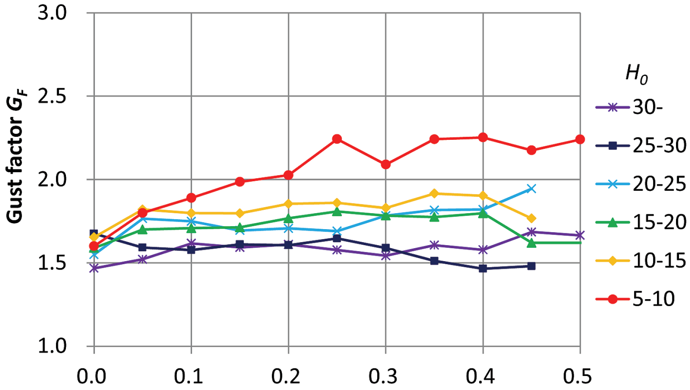
(c) Average height of buildings $\overline{h}$



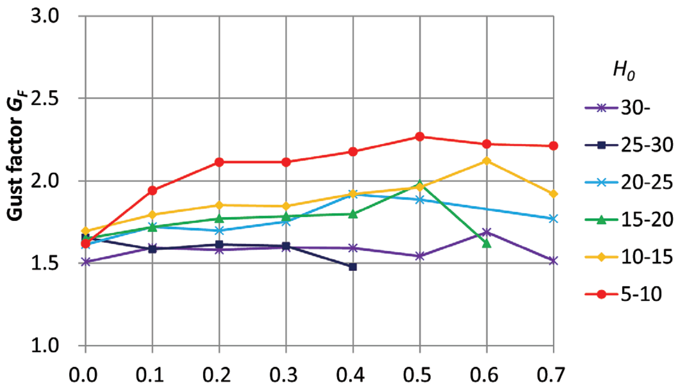
(d) Ratio of high building area $\overline{h_4}$

Fig. 7 (cont). Relationship between G_F and surface roughness classified into several height classes

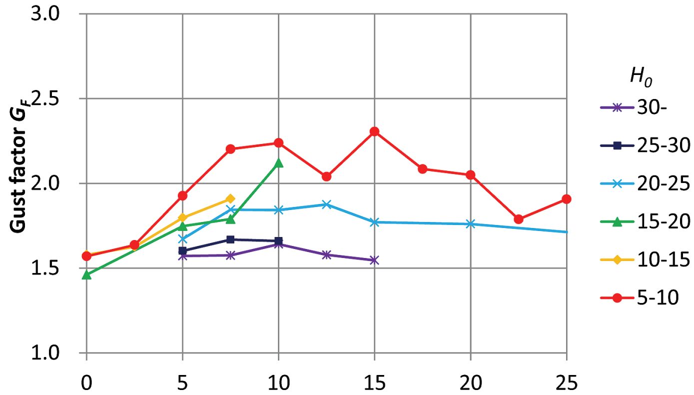
To investigate the influence of H_O on G_F in more detail, the average value of G_F for each class of height was plotted against each factor of surface roughness, as shown in Fig. 8. As shown in Fig. 8(a), when H_O is less than about 20 m, the value of G_F first increases and then reaches a constant value as R_b increases. The constant value of G_F depends on H_O. For example, when H_O is within the range from 5 m to 10 m, the value of G_F is approximately 2.2 to 2.3. This constant value decreases as H_O increases. When H_O is greater than about 25 m, the value of G_F is only very slightly affected by R_b. A similar effect can be seen for the other factors, particularly for R_b and V_b, the values of which vary over a wide range. The value of G_F is approximately 1.5 to 1.6 regardless of the value of H_O, as the value of each factor approaches zero. It was found that both the observation height and the surface roughness factors significantly affect the characteristics of G_F.



(a) Building coverage ratio R_b

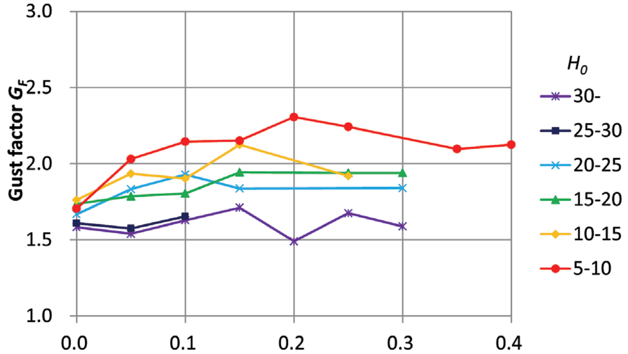


(b) Building volume ratio V_b



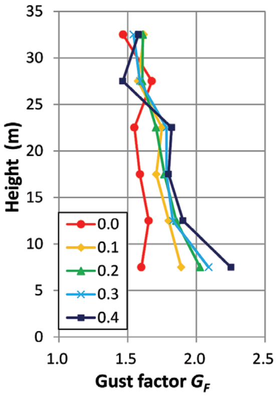
(c) Average height of buildings $\overline{h}$

Fig. 8. Average value of G_F for each class of height against each factor of surface roughness

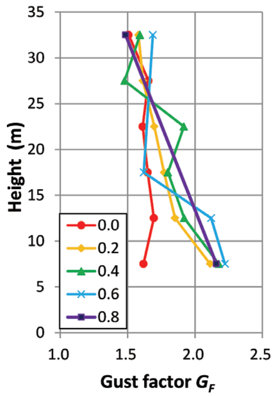


(d) Ratio of high buildings area $\overline{h_4}$

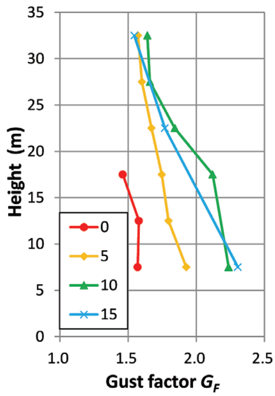
Fig. 8 (cont.). Average value of G_F for each class of height against each factor of surface roughness



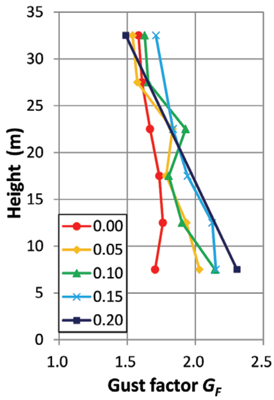
(a) R_b



(b) V_b



(c) $\overline{h}$



(d) $\overline{h_4}$

Fig. 9. Relationship between H_O and G_F for each factor

Fig. 9 illustrates the relationship between H_O and G_F for each factor. In this figure, the values of each factor are divided into several classes and the average values are plotted. It was found that the variation of G_F with H_O becomes more significant as the value of each factor increases. Furthermore, G_F is greatly affected by the surface roughness when H_O is low. With this increase in H_O, G_F becomes less sensitive to the surface roughness factors.

Therefore, the authors suggest that G_F can be defined by the values of the surface roughness parameters such as R_b and the height.

4. Conclusions

The relationship between the surface roughness characteristics and the gust factor has been discussed based on data obtained from measurements taken in the field and a building information database. It was found that some surface roughness factors, such as the building coverage ratio, are closely related to the gust factor when $H_O < 15$ m. Furthermore, the observation height also has a significant effect on the gust factor. The gust factor can be given by a function of these factors and the height above the ground.

In future work, to investigate this relationship in more detail, statistical analysis, such as multivariate analysis, will be applied to the data. Variation in the turbulence will be taken into consideration. Furthermore, it is intended to investigate the relationship between the gust factor and the turbulence of the wind like turbulence intensity based on measurements and wind tunnel tests using a variety of surface roughnesses.

References

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